New results on catalyzed BBN with a long-lived negatively-charged massive particle

Motohiko Kusakabe[1*] and Toshitaka Kajino[2,3,4], Takashi Yoshida[3] and Grant J. Mathews[5]
[1] *Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba 277-8582, Japan*
[2] *Division of Theoretical Astronomy, National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan*
[3] *Department of Astronomy, Graduate School of Science, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[4] *Department of Astronomical Science, The Graduate University for Advanced Studies, Mitaka, Tokyo 181-8588, Japan*
[5] *Department of Physics, Center for Astrophysics, University of Notre Dame, Notre Dame, IN 46556, USA*

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It has been proposed that the apparent discrepancies between the inferred primordial abundances of ^{6}Li and ^{7}Li and the predictions of big bang nucleosynthesis (BBN) can be resolved by the existence of a negatively-charged massive unstable supersymmetric particle (X^-) during the BBN epoch. Here, we present new BBN calculations with an X^- particle utilizing an improved nuclear reaction network including captures of nuclei by the particle, nuclear reactions and β-decays of normal nuclei and nuclei bound to the X^- particles (X-nuclei), and new reaction rates derived from recent rigorous quantum many-body dynamical calculations. We find that this is still a viable model to explain the observed ^{6}Li and ^{7}Li abundances. However, contrary to previous results, neutral X-nuclei cannot significantly affect the BBN light-element abundances. We also show that with the new rates the production of heavier nuclei is suppressed and there is no signature on abundances of nuclei heavier than Be in the X^--particle catalyzed BBN model as has been previously proposed. We also consider the version of this model whereby the X^- particle decays into the present cold dark matter. We analyze the this paradigm in light of the recent constraints on the dark-matter mass deduced from the possible detected events in the CDMS-II experiment. We conclude that based upon the inferred range for the dark-matter mass, only X^- decay via the weak interaction can achieve the desired ^{7}Li destruction while also reproducing the observed ^{6}Li abundance.

The nucleosynthesis of light elements in the big bang is a unique probe of new physics which may have occurred during the first few minutes of cosmic expansion in the big bang. Of particular interest in this work is the apparent discrepancy between the inferred primordial abundances of ^{6}Li and ^{7}Li and the predictions of standard BBN. A popular model to resolve this discrepancy is the existence of an unstable negatively charged supersymmetric particle during the nucleosynthesis epoch [1–13]. Depending upon their abundance and lifetime [7], such particles can catalyze the nuclear reactions leading to enhanced ^{6}Li [1] and depleted ^{7}Li [5, 6] as required by observations. Here we present new calculations based upon a substantially improved nuclear reaction network for this X^--catalyzed BBN. We solve numerically the nonequilibrium nuclear and chemical reaction network associated to the X^- particle [7] with improved reaction rates derived from recent rigorous quantum many-body dynamical calculations [9]. We show that both the ^{6}Li and ^{7}Li problems can still be solved. However, contrary to earlier speculation [10], there is no signature in the primordial abundances of heavier nuclides produced by this mechanism.

Also in this work we examine the version of this model in which the X^- particles decay into the present dark matter. In such models the allowed lifetimes and abundances can be sensitive to the mass of the dark-matter particle. In this regard the recent results of the Cryogenic Dark Matter Search experiment (CDMS II) are of interest. Possible detected events imply an upper limit on the elastic scattering spin-independent cross section between the weakly interacting massive particle (WIMP) and the nucleon [14]. Based upon this, they have identified an allowed parameter region of the WIMP mass of 40 GeV $< m_{\rm DM} <$ 200 GeV which is consistent with both the CDMS II experiment and the DAMA/LIBRA data. We discuss the implication of this mass constraint and show that the ^{7}Li problem can still be resolved together with the ^{6}Li abundance, but only if the negatively charged particles decay into a lighter dark-matter particle via a weak charged boson exchange.

The primordial lithium abundances can be inferred from measurements of absorption line profiles in metal-poor stars (MPSs). These stars exhibit roughly constant values of the abundance ratio, ^{7}Li/H, as a function of metallicity [15–21] implying a primordial abundance of ^{7}Li/H$= (1-2)\times 10^{-10}$. The standard BBN model, however, predicts a value that is a factor of $2-4$ higher (e.g., ^{7}Li/H$=(5.24^{+0.71}_{-0.67})\times 10^{-10}$ [22]) when one uses the baryon-to-photon ratio determined from an analysis [23] of data from the Wilkinson Microwave Anisotropy Probe (WMAP) of the cosmic microwave background (CMB) radiation. This discrepancy requires a mechanism to reduce the ^{7}Li abundance inferred from BBN. The combination of atomic and turbulent diffusion [24, 25] might have reduced the ^{7}Li abundance in stellar atmospheres, but this possibility has not yet been established [26].

An even more intriguing result concerns the ^{6}Li/^{7}Li

*kusakabe@icrr.u-tokyo.ac.jp

isotopic ratios for MPSs. These have been determined [18] and a high ^{6}Li abundance of ^{6}Li/H$\sim 6\times10^{-12}$ has been suggested. This is $\sim$1000 times higher than the standard BBN prediction. One should be cautious, however, in interpreting these results in that convective motion in stellar atmospheres could cause systematic asymmetries in the observed stellar line profiles and thereby mimic the presence of ^{6}Li [27]. Nevertheless, several MPSs, continue to exhibit high ^{6}Li abundances even after carefully correcting for the convection-triggered line asymmetries [28].

Be and B abundances have also observed in MPSs. ^{9}Be [29–34] and B [35–38] abundances appear to increase roughly linearly as the Fe abundance increases. The absence of a plateau in the abundances of Be and B at low metallicity, however, suggests that these elements are not of primordial origin.

Nonthermal nuclear reactions induced by the decay of exotic particles have been studied [39, 40] as a means to provide a cosmological solution to the Li problems. Nonthermal reactions triggered by the radiative decay of long-lived particles can produce ^{6}Li nuclides up to a level ~ 10 times larger than the observed level without causing discrepancies in abundances of other light nuclei or the CMB energy spectrum [40].

Another solution to the lithium problems of particular interest here is that due to the presence of negatively charged massive particles X^- [41–43] during the BBN epoch. They affect the nucleosynthesis in a different way [1–13]. The X^- particles become electromagnetically bound to positively charged nuclides with binding energies of $\sim O(0.1-1)$ MeV with the largest binding energies for heavier nuclei with larger charges. Since these binding energies are low, the bound states cannot form until late in the BBN epoch. At the low temperatures associated with late times, nuclear reactions are no longer efficient. Hence, the effect of the X^- particles is rather small. Interestingly, however, the X^- particles can catalyze the preferential production of ^{6}Li [1] along with the weak destruction of ^{7}Be [5, 6].

A large enhancement of the ^{6}Li abundance was first suggested [1] to result from an X^- bound to ^{4}He (denoted as ^{4}He$_X$). This enables the X^--catalyzed transfer reaction of ^{4}He$_X(d,X^-)^6$Li, whose cross section could be seven orders of magnitude larger than the corresponding BBN ^{4}He$(d,\gamma)^6$Li reaction. The cross section for this reaction, however, was calculated in a more rigorous quantum three-body model [4] and shown to be about an order of magnitude smaller than the estimate adopted in Ref. [1].

Additional enhancements in X^--catalyzed transfer reaction rates for the ^{4}He$_X(t,X^-)^7$Li, ^{4}He$_X(^3$He$,X^-)^7$Be, and ^{6}Li$_X(p,X^-)^7$Be reactions were assumed in Ref. [3]. The rates for those reactions are, however, not as greatly enhanced as that of the ^{4}He$_X(d,X^-)^6$Li because they involve a $\Delta l = 1$ angular momentum transfer and consequently a large hindrance of the nuclear matrix element [6]. This has been confirmed in recent detailed quantum many-body calculations [9].

The resonant ^{7}Be$_X(p,\gamma)^8$B$_X$ reaction through the first atomic excited state of ^{8}B$_X$ was suggested [5] as a means to reduce the primordial ^{7}Li abundance [51]. A rate for this reaction has been calculated in a rigorous quantum three body model [9], which roughly reproduces the value of Ref. [5] but is somewhat inefficient in destroying ^{7}Be$_X$. The resonant reaction ^{7}Be$_X+p \rightarrow {}^8$B$^*(1^+$, 0.770 MeV$)_X \rightarrow {}^8$B$_X+\gamma$ through the atomic ground state of ^{8}B$^*(1^+$,0.770 MeV$)_X$, i.e., an atom consisting of the 1^+ nuclear excited state of ^{8}B and an X^- particle has also been proposed [6] as a process for ^{7}Be$_X$ destruction. From a more realistic estimate of binding energies between nuclides and X^- particles [7], this resonant reaction was found to exist, but the resonance energy level is too high to efficiently destroy ^{7}Be$_X$.

The ^{8}Be$_X+p \rightarrow {}^9$B$^{*a}_X \rightarrow {}^9$B$_X+\gamma$ reaction through the ^{9}B$^{*a}_X$ atomic excited state of ^{9}B$_X$ has also been studied [7]. However this reaction was found to be not operative because its resonance energy is relatively large (see Table 2 of Ref. [7]). A resonant reaction ^{8}Be$_X(n,X^-)^9$Be through the atomic ground state of ^{9}Be$^*(1/2^+$,1.684 MeV$)_X$, i.e., an atom composed of the 1/2+ nuclear excited state of ^{9}Be and an X^- particle, has also been suggested as a possible reaction to produce mass 9 nuclides [10]. Kamimura et al. [9], however, adopted a root mean square charge radius for ^{8}Be of 3.39 fm as a more realistic input. They then found that ^{9}Be$^*(1/2^+$, 1.684 MeV$)_X$ is not a resonance but a bound state located below the ^{8}Be$_X+n$ threshold. The resonant ^{8}Be$_X(n,X^-)^9$Be$_X$ reaction is thus not likely to contribute.

Neutral X-nuclei, i.e., p_X, d_X and t_X have also been suggested [8] as a means to produce and destroy Li and Be through two α-induced X^- stripping reactions $d_X(\alpha,X^-)^6$Li and $t_X(\alpha,X^-)^7$Li, and three p_X induced stripping reactions $p_X(^6$Li$,^3$He$\alpha)X^-$, $p_X(^7$Li$,2\alpha)X^-$ and $p_X(^7$Be$,^8$B$)X^-$. The result, however, relies on reaction rates calculated within the framework of the Born approximation, which is a poor approximation in this low-energy regime [9, 42]. The rates for those reactions and those for charge-exchange reactions of $p_X(\alpha,p)\alpha_X$, $d_X(\alpha,d)\alpha_X$ and $t_X(\alpha,t)\alpha_X$ have been calculated in a rigorous dynamical quantum many-body treatment in Ref. [9]. They found that the cross sections for the charge-exchange reactions were much larger than those of the nuclear reactions, and that the neutral bound states p_X, d_X and t_X were immediately changed to α_X before they could react with ambient nuclei. The late time production and destruction of Li and Be, therefore, do not significantly affect the BBN as shown in this letter.

The solution to the lithium problems in this catalyzed BBN model have been explored by solving the full Boltzmann equations for the recombination and the ionization of nuclides and X^- particles coupled to the nuclear reactions [6–8]. Constraints on specific supersymmetric models through the catalyzed BBN calculation have been obtained in Refs. [3, 11, 12, 44, 45].

Candidates for the leptonic X^- particle of interest in these models are the spin 0 supersymmetric partners of the standard-model leptons. Such X^- particles (and their antiparticles X^+) would be produced copiously in the hot early universe and subsequently annihilate. Their annihilations, however, would freezeout at some epoch. The residual X^+ particles do not affect BBN because they do not bind to the positively-charged nuclei. It is possible, however, that the decay of both $X^\pm$ particles affect the final light element abundances through electromagnetic and/or hadronic showers. Here, however, we only consider the X-nuclear reactions, and not the effect of subsequent decay.

The binding energies of nuclei bound to X^- particles, i.e., X-nuclei, have been derived by taking account of the modified Coulomb interaction with the nucleus [7] under the assumption that the mass of the X^- particle is much heavier than the nucleon mass.

We performed the detailed network calculation of the catalyzed BBN [7] taking into account both the recombination and ionization of X^- particles with nuclei and thermonuclear reactions and β-decay of normal nuclides and X-nuclei. We adopt all of the new reaction rates from the rigorous quantum many-body dynamical calculations of Ref. [9]. For the ${}^7\mathrm{Be}_X(p,\gamma){}^8\mathrm{B}_X$ resonant reaction through an atomic excited state of ${}^8\mathrm{B}_X$, rates for different masses of X^- have been published [9]. For our purposes we adopt their rate for an infinite X^- mass. Our results are thus completely different from previous studies without the use of the new cross sections.

We adopt the constraint on the primordial ^{6}Li abundance from the observations in MPSs. The primordial abundances of ^{6}Li and ^{7}Li could be higher than the observed abundances [18] considering the possible effect of stellar depletion of initial surface abundances. The observed abundances should, therefore, be considered a lower limit to the true primordial ones. Since ^{6}Li is more fragile to nuclear burning than ^{7}Li [24], its depletion factors could be larger than those for ^{7}Li. We adopt a conservative limit of a factor of 10 above the mean value of $({}^6\mathrm{Li/H})_{\mathrm{MPS}} = (7.1 \pm 0.7) \times 10^{-12}$ [18], and a 3 σ lower limit to the mean value times a factor of 1/3. The limit on the ^{6}Li/H abundance are thus $1.7 \times 10^{-12} \leq {}^6\mathrm{Li/H} \leq 7.1 \times 10^{-11}$.

Figures 1a and 1b show the results of a catalyzed BBN calculation. For these figures the X^- abundance was taken to be 5% of the total baryon abundance, i.e. $Y_X = n_X/n_b = 0.05$, where n_X and n_b are the number densities of the X^- particles and baryons, respectively. Figure 1a shows the evolution of normal nuclei while Figure 1b corresponds to X-nuclei.

The abundances of the normal nuclei are very similar to the standard BBN abundances until the temperature reaches $T_9 \sim 0.5$. The X^- particles then combine with ^{7}Be at $T_9 \sim 0.5$ and subsequently ^{7}Li at $T_9 \sim 0.3$. The ${}^7\mathrm{Be}_X$ produced by these X^- captures (Fig. 1b) is then destroyed by the ${}^7\mathrm{Be}_X(p,\gamma){}^8\mathrm{B}_X$ reaction, primarily through the atomic excited state of ${}^8\mathrm{B}_X$ [5], and secondarily through the atomic ground state ${}^8\mathrm{B}^*(1^+, 0.770\ \mathrm{MeV})_X$ composed of the ${}^8\mathrm{B}^*(1^+, 0.770$ MeV) nuclear excited state and an X^- particle [6]. We have assumed that ${}^8\mathrm{B}_X$ inter-converts to ${}^8\mathrm{Be}^*(2^+,3\ \mathrm{MeV})_X$ by β-decay with a rate given by the normal ^{8}B β-decay rate multiplied by a correction term $(Q_X/Q)^5$, where Q and Q_X are the Q-values of the standard β-decay and that of β-decay for X-nuclei [7]. The produced ${}^8\mathrm{Be}^*(2^+,3\ \mathrm{MeV})_X$ then immediately decays to the three-body channel $\alpha+\alpha+X^-$ [9].

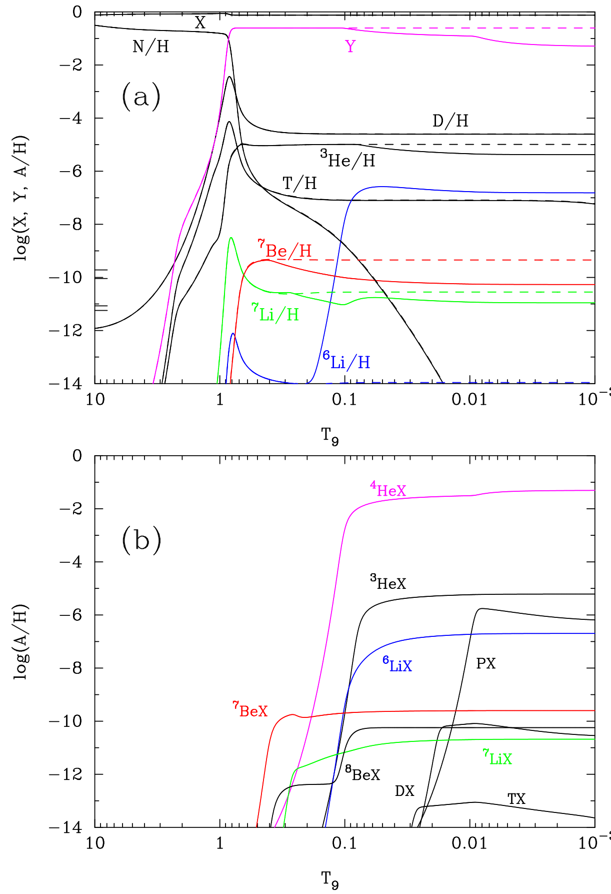

FIG. 1: (color online). Calculated abundances of normal nuclei (a) and X-nuclei (b) as a function of T_9 (solid lines). The abundance and the lifetime of the X^- particle are set to be $Y_X = n_X/n_b = 0.05$ and $\tau_X = \infty$, respectively. The dashed lines correspond to the standard BBN case.

When the temperature decreases to $T_9 \sim 0.1$, the X^- particles bind to ^{4}He. Then, the X^--catalyzed transfer reaction ${}^4\mathrm{He}_X(d,X^-)$ operates to produce normal ^{6}Li and ${}^6\mathrm{Li}_X$ (after the recombination). Because of the small binding energies to the X^- (see Table I of Ref. [7]), neutral X-nuclei do not form until late times corresponding to $T_9 \sim 0.03$ (for t_X), $T_9 \sim 0.02$ (for d_X) and $T_9 \sim 0.01$ (for p_X). The neutral X-nuclei then mainly react with ^{4}He nuclei to lose their X^- and to produce ${}^4\mathrm{He}_X$ (as a result of the precise calculation [9]) so that abundances of neutral X-nuclei are kept low. Nuclear reactions triggered by neutral X-nuclei are thus not important.

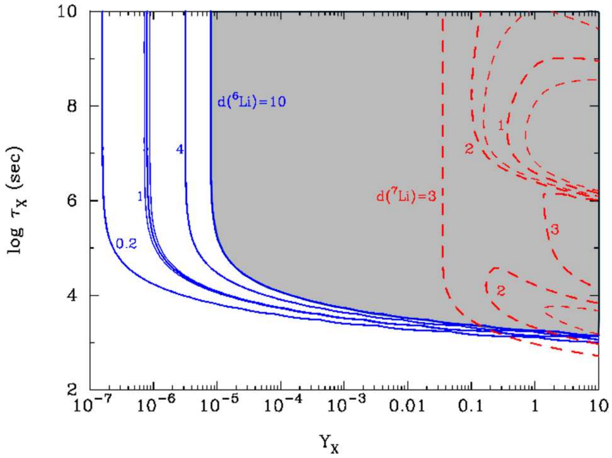

FIG. 2: (color online). Contours of constant lithium isotopic abundances relative to observed values in MPSs, i.e., $d(^6\mathrm{Li}) = {}^6\mathrm{Li}^{\mathrm{Calc}}/{}^6\mathrm{Li}^{\mathrm{Obs}}$ (solid curves) and $d(^7\mathrm{Li}) = {}^7\mathrm{Li}^{\mathrm{Calc}}/{}^7\mathrm{Li}^{\mathrm{Obs}}$ (dashed curves). The adopted observational abundances are ^{7}Li/H= $(1.23^{+0.68}_{-0.32}) \times 10^{-10}$ [16] and ^{6}Li/H= $(7.1 \pm 0.7) \times 10^{-12}$ [18]. Thin solid and dashed lines around the lines of $d(^{6,7}\mathrm{Li}) = 1$ correspond to the 1 σ uncertainties in the observational constraint. The gray region is observationally excluded by the overproduction of ^{6}Li.

Figure 2 shows the contours of $d(^6\mathrm{Li})$ (solid curves) and $d(^7\mathrm{Li})$ (dashed curves) in the parameter plane of the abundance Y_X and the lifetime τ_X of the X^- particles. $d(^A\mathrm{Li})={}^A\mathrm{Li}^{\mathrm{Calc}}/{}^A\mathrm{Li}^{\mathrm{Obs}}$ is the ratio of the calculated abundance to the observed abundance. The solid curves labeled $d(^6\mathrm{Li})$=10 and 0.2 correspond to upper and lower limits on the abundance constraint ($1.7 \times 10^{-12} \leq {}^6\mathrm{Li/H} \leq 7.1 \times 10^{-11}$). Above the $d(^6\mathrm{Li})$=0.2 line, ^{6}Li is produced at the observed level in MPSs.

The thick dashed curves are for $d(^7\mathrm{Li})$=1, 2 and 3. The dashed curve for $d(^7\mathrm{Li})$=2 intersects the contours of $d(^6\mathrm{Li})$ for $Y_X \gtrsim 1$ and $\tau_X \approx (1-2) \times 10^{-3}$. In the region above this curve the ^{7}Li abundance is lower than $^7\mathrm{Li/H} \approx 2.5 \times 10^{-10}$. The updated parameter region for a simultaneous solution to the ^{6}Li and ^{7}Li abundances in BBN with negatively charged particle is: $Y_X \gtrsim 1$ and $\tau_X \approx (1-2) \times 10^3$ s.

For $\tau_X \gtrsim 10^4$ s and $Y_X \gtrsim 0.3$, the calculated abundance of ^{7}Li increases slightly due to the $^4\mathrm{He}_X(t,X^-)^7\mathrm{Li}$ and $^4\mathrm{He}_X(^3\mathrm{He},X^-)^7\mathrm{Be}$ reactions which produce some amount of ^{7}Li. However, this parameter region is not allowed due to an extreme overproduction of ^{6}Li. The gray region in Fig. 2 is the parameter region excluded by the overproduction of ^{6}Li.

If the X^- particle decays via the weak interaction, $^7\mathrm{Be}_X$ converts to ^{7}Li by a weak charged current transition from X^- to X^0, i.e. $^7\mathrm{Be}_X \to {}^7\mathrm{Li}+X^0$ [5, 12]. This case is shown in Fig. 6 of Ref. [7]. The results from that study do not change by the implementation of the new cross sections adopted here. The larger destruction rate associated with the $^7\mathrm{Be}_X \to {}^7\mathrm{Li}+X^0$ decay followed by the $^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$ and $^7\mathrm{Li}(X^-,\gamma)^7\mathrm{Li}_X(p,2\alpha)X^-$ reactions [5, 7] or a further conversion of $^7\mathrm{Li}_X$ by the weak interaction [12] shifts the contours of the ^{7}Li abundance toward smaller values of Y_X. In this case the parameter region which solves both the ^{6}Li and ^{7}Li problems is $Y_X \approx 0.04 - 0.2$ and $\tau_X \approx (1.4-2.6) \times 10^3$ s.

We now consider a model in which the present cold dark matter (DM) was produced by the decay of $X^\pm$ particles, i.e., $Y_{\mathrm{DM}} \geq Y_X$. The WMAP-CMB constraint on the cosmological density parameter of cold DM $\Omega_{\mathrm{CDM}} = 0.2$ then corresponds to $m_{\mathrm{DM}} Y_{\mathrm{DM}} \leq 4.5$ GeV. The constraints on Y_X required to resolve the ^{6}Li and ^{7}Li problems then imply a range for the the dark-matter mass m_{DM}. In the case where the reactions $^7\mathrm{Be}_X+p \to {}^8\mathrm{B}^{*a}_X \to {}^8\mathrm{B}_X+\gamma$ [5] and $^7\mathrm{Be}_X + p \to {}^8\mathrm{B}^*(1^+, 0.770\ \mathrm{MeV})_X \to {}^8\mathrm{B}_X + \gamma$ [6] destroy $^7\mathrm{Be}_X$, the DM mass is thus constrained to be $m_{\mathrm{DM}} \leq 4.5$ GeV. On the other hand, when the $^7\mathrm{Be}_X \to {}^7\mathrm{Li}+X^0$ reaction [5, 12] is included, the allowed mass range increases to $m_{\mathrm{DM}} \leq 20 - 110$GeV.

Comparing this result to the allowed parameter region for the DM mass of 40 GeV $< m_{\mathrm{DM}} <$ 200 GeV [14], implies that only an X^- particle which decay via the weak interaction can have existed with sufficient abundance to reduce ^{7}Li produced from BBN. On the other hand, if the X^- particles do not decay via the weak interaction they are excluded.

In summary, we have re-investigated BBN in the presence of negatively-charged massive particles X^- by solving the rate equations with an improved nuclear reaction network code [7]. We have adopted the newest quantum many-body dynamical calculations [9]. With the new rates, we find that, contrary to the speculation in previous studies, the neutral X-nuclei, i.e., p_X, d_X and t_X, do not significantly affect the BBN abundances. Furthermore, based upon constraints for the mass of DM particles from the possible CDMS-II events we conclude that only X^- particles which decay into the DM via the weak interaction can simultaneously reduce ^{7}Li to the desired level while producing enough ^{6}Li in the early universe.

Finally, we note that in this revised catalyzed BBN model there is no signature in the abundances of nuclei heavier than Be. Thus, if one were to find a primordial plateau abundance of Be or B, it would require an origin other than this catalyzed BBN model. There are three physical processes by which enhanced abundances of nuclei heavier than Be could have been formed. The first is the cosmological cosmic ray nucleosynthesis induced by supernova explosions during an early epoch of structure formation [46]. This model can resolve the ^{6}Li problem and leave possible abundance plateaus of ^{9}Be and B [47, 48]. The second is the BBN model including a long-lived strongly interacting massive particle. Signatures of such particles are possibly left on the primordial abundances of Be and B which may be found in future astronomical observations of MPSs [49]. The third is the inhomogeneous BBN model which can lead to a high primordial abundance of ^{9}Be [50].

Acknowledgments

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[1] M. Pospelov, Phys. Rev. Lett. **98**, 231301 (2007).
[2] K. Kohri and F. Takayama, Phys. Rev. D **76**, 063507 (2007).
[3] R. H. Cyburt, J. R. Ellis, B. D. Fields, K. A. Olive and V. C. Spanos, JCAP **0611**, 014 (2006).
[4] K. Hamaguchi, T. Hatsuda, M. Kamimura, Y. Kino and T. T. Yanagida, Phys. Lett. B **650**, 268 (2007).
[5] C. Bird, K. Koopmans and M. Pospelov, Phys. Rev. D **78**, 083010 (2008).
[6] M. Kusakabe, T. Kajino, R. N. Boyd, T. Yoshida and G. J. Mathews, Phys. Rev. D **76**, 121302 (2007).
[7] M. Kusakabe, T. Kajino, R. N. Boyd, T. Yoshida and G. J. Mathews, Astrophys. J. **680**, 846 (2008).
[8] K. Jedamzik, Phys. Rev. D **77**, 063524 (2008); K. Jedamzik, JCAP **0803**, 008 (2008).
[9] M. Kamimura, Y. Kino and E. Hiyama, Prog. Theor. Phys. **121**, 1059 (2009).
[10] M. Pospelov, arXiv:0712.0647 [hep-ph].
[11] M. Kawasaki, K. Kohri and T. Moroi, Phys. Lett. B **649**, 436 (2007).
[12] T. Jittoh, K. Kohri, M. Koike, J. Sato, T. Shimomura and M. Yamanaka, Phys. Rev. D **76**, 125023 (2007); Phys. Rev. D **78**, 055007 (2008).
[13] M. Pospelov, J. Pradler and F. D. Steffen, JCAP **0811**, 020 (2008).
[14] Z. Ahmed *et al.* [The CDMS-II Collaboration and CDMS-II Collaboration], arXiv:0912.3592 [astro-ph.CO].
[15] F. Spite and M. Spite, Astron. Astrophys. **115**, 357 (1982).
[16] S. G. Ryan, S. G. Ryan, T. C. Beers, K. A. Olive, B. D. Fields and J. E. Norris, Astrophys. J. **530**, L57 (2000).
[17] J. Melendez and I. Ramirez, Astrophys. J. **615**, L33 (2004).
[18] M. Asplund, D. L. Lambert, P. E. Nissen, F. Primas and V. V. Smith, Astrophys. J. **644**, 229 (2006).
[19] P. Bonifacio *et al.*, Astron. Astrophys. **462**, 851 (2007).
[20] J. R. Shi, T. Gehren, H. W. Zhang, J. L. Zeng, J. L. and G. Zhao, Astron. Astrophys. **465**, 587 (2007).
[21] W. Aoki *et al.*, Astrophys. J. **698**, 1803 (2009).
[22] R. H. Cyburt, B. D. Fields and K. A. Olive, JCAP **0811**, 012 (2008).
[23] J. Dunkley *et al.* [WMAP Collaboration], Astrophys. J. Suppl. **180**, 306 (2009).
[24] O. Richard, G. Michaud and J. Richer, Astrophys. J. **619**, 538 (2005).
[25] A. J. Korn *et al.*, Astrophys. J. **671**, 402 (2007).
[26] K. Lind, F. Primas, C. Charbonnel, F. Grundahl and M. Asplund, Astron. Astrophys. **503**, 545 (2009).
[27] R. Cayrel *et al.*, Astron. Astrophys. **473**, L37 (2007).
[28] A. E. G. Perez, W. Aoki, S. Inoue, S. G. Ryan, T. K. Suzuki and M. Chiba, Astron. Astrophys. **504**, 213 (2009); M. Steffen, R. Cayrel, P. Bonifacio, H. G. Ludwig and E. Caffau, arXiv:0910.5917 [astro-ph.SR].
[29] A. M. Boesgaard, C. P. Deliyannis, J. R. King, S. G. Ryan, S. S. Vogt and T. C. Beers, Astron. J. **117**, 1549 (1999).
[30] F. Primas, P. Molaro, P. Bonifacio and V. Hill, Astron. Astrophys. **362**, 666 (2000).
[31] K. F. Tan, J. R. Shi and G. Zhao, Mon. Not. Roy. Astron. Soc. **392**, 205 (2009).
[32] R. Smiljanic, L. Pasquini, P. Bonifacio, D. Galli, R. G. Gratton, S. Randich and B. Wolff, Astron. Astrophys. **499**, 103 (2009).
[33] H. Ito, W. Aoki, S. Honda and T. C. Beers, Astrophys. J. **698**, L37 (2009).
[34] J. A. Rich and A. M. Boesgaard, Astrophys. J. **701**, 1519 (2009).
[35] D. K. Duncan, F. Primas, L. M. Rebull, A. M. Boesgaard, C. P. Deliyannis, L. M. Hobbs, J. R. King and S. G. Ryan, Astrophys. J. **488**, 338 (1997).
[36] R. J. Garcia Lopez, D. L. Lambert, B. Edvardsson, B. Gustafsson, D. Kiselman, and R. Rebolo, R. Astrophys. J. **500**, 241 (1998).
[37] F. Primas, D. K. Duncan, R. C. Peterson and J. A. Thorburn, Astron. Astrophys. **343**, 545 (1999).
[38] K. Cunha, V. V. Smith, A. M. Boesgaard and D. L. Lambert, Astrophys. J. **530**, 939 (2000).
[39] J. Ellis, D. V. Nanopoulos, and S. Sarkar, Nucl. Phys. B **259**, 175 (1985); M. H. Reno and D. Seckel, Phys. Rev. D **37**, 3441 (1988); S. Dimopoulos *et al.*, Astrophys. J. **330**, 545 (1988); M. Kawasaki *et al.*, Nucl. Phys. B **419**, 105 (1994); M. Y. Khlopov *et al.*, Phys. Atom. Nucl. **57**, 1393 (1994); M. Kawasaki and T. Moroi, Prog. Theor. Phys. **93**, 879 (1995); E. V. Sedelnikov, S. S. Filippov and M. Y. Khlopov, Phys. Atom. Nucl. **58**, 235 (1995); K. Jedamzik, Phys. Rev. Lett. **84**, 3248 (2000); M. Kawasaki, K. Kohri and T. Moroi, Phys. Rev. D **63**, 103502 (2001); R. H. Cyburt *et al.*, Phys. Rev. D **67**, 103521 (2003); K. Jedamzik, Phys. Rev. D **70**, 063524 (2004); M. Kawasaki, K. Kohri and T. Moroi, Phys. Rev. D **71**, 083502 (2005); J. R. Ellis, K. A. Olive and E. Vangioni, Phys. Lett. B **619**, 30 (2005); K. Jedamzik, Phys. Rev. D **74**, 103509 (2006); D. Cumberbatch *et al.*, Phys. Rev. D **76**, 123005 (2007); K. Kohri and Y. Santoso, Phys. Rev. D **79**, 043514 (2009).
[40] M. Kusakabe, T. Kajino and G. J. Mathews, Phys. Rev. D **74**, 023526 (2006); M. Kusakabe, T. Kajino, T. Yoshida, T. Shima, Y. Nagai and T. Kii, Phys. Rev. D **79**, 123513 (2009).
[41] R. N. Cahn and S. L. Glashow, Science **213**, 607 (1981).
[42] S. Dimopoulos, D. Eichler, R. Esmailzadeh and G. D. Starkman, Phys. Rev. D **41**, 2388 (1990).
[43] A. de Rújula, S. L. Glashow and U. Sarid, Nucl. Phys. B **333**, 173 (1990).
[44] M. Kawasaki, K. Kohri, T. Moroi and A. Yotsuyanagi, Phys. Rev. D **78**, 065011 (2008).
[45] S. Bailly, K. Jedamzik and G. Moultaka, Phys. Rev. D

80, 063509 (2009); K. Jedamzik and M. Pospelov, New J. Phys. **11**, 105028 (2009).

[46] E. Rollinde, E. Vangioni-Flam and K. A. Olive, Astrophys. J. **627**, 666 (2005).

[47] M. Kusakabe, Astrophys. J. **681**, 18 (2008).

[48] E. Rollinde, D. Maurin, E. Vangioni, K. A. Olive and S. Inoue, Astrophys. J. **673** 676 (2008).

[49] M. Kusakabe, T. Kajino, T. Yoshida and G. J. Mathews, Phys. Rev. D **80**, 103501 (2009).

[50] T. Kajino and R. N. Boyd, Astrophys. J. **359** 267 (1990); M. Orito, T. Kajino, R. N. Boyd and G. J. Mathews, Astrophys. J. **488** 515 (1997).

[51] In standard BBN with the baryon-to-photon ratio inferred from WMAP, ^{7}Li is produced mostly as ^{7}Be during the BBN epoch. Subsequently, ^{7}Be is transformed into ^{7}Li by electron capture.